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Rb-Sr Geochronology and Petrogenesis of the Late Mesozoic Igneous Rocks in the Inner Zone of the Southwestern Part of Japan

By

Tatsuya SEKI*

(Received August 30, 1977)

Abstract

Rb-Sr isotopic measurements have been made on Cretaceous intermediate-acid igneous rocks from four districts, Yamaguchi, Himeji, Koto and Nohi, of the inner zone of southwest Japan, and more than ten whole rock and internal isochrons have been obtained.

Isochron ages of about 110 m.y. have been obtained from volcanic rocks of all of four districts. Another age of volcanic activity is about 70 m.y. The age of granitic rocks obtained is about 80-90 m.y.

Initial Sr isotope ratios range from 0.7051 to 0.7103. The variation of these initial Sr ratios is more closely related with the crustal structure than with the age. Rb/Sr ratios (0.05-24) are higher than those of other calc-alkaline rocks of circum-Pacific regions. These data have been interpreted as that the parental magmas were generated from old lower crustal materials.

Local geochronology, space-time relations of the igneous activity, the age of the "Roseki" deposits and the relation between age and paleomagnetism are discussed in detail.

I Introduction

In the Japanese Islands the igneous rocks of intermediate to acid composition (volcanic-plutonic complex) erupted or intruded in all part of the inner zone of southwest Japan mainly during the late Mesozoic era (RGLM**, 1967; ICHIKAWA *et al.*, 1968). The total volume of volcanic products was estimated to be up to 10^5 km^3 (RGLM, 1967). Recently more detailed petrographical studies on these rocks have been done in many districts and it is noticed that the distribution areas are extended to more eastern part of the Honshu Island (YANAI *et al.*, 1973). To search for the petrogenesis of these rocks, it is necessary to investigate exactly the geologic ages, as well as the geology and geochemistry.

In the past fifteen years a lot of radiometric age determinations have been carried out in Japan mainly by K-Ar and Rb-Sr methods (KAWANO and UEDA, 1967; HAYASE and ISHIZAKA, 1967; SHIBATA, 1968; ISHIZAKA and YAMAGUCHI, 1969; SHIBATA and ADACHI, 1974). The age results offered important informations about the geological development of Japanese Islands. However, there had been done few age determi-

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** RGLM=Research group for late Mesozoic igneous activity of southwest Japan

nations for the volcanic rocks of Mesozoic age. The main reason of this is due to the fact that these volcanic rocks have no or few minerals which are useful for the radiometric age determinations (e.g. mica or K-feldspar). Therefore the time of eruption of the volcanic rocks was often indirectly estimated from the geological relations to the granitic rocks whose isotopic ages had already been known. However, it is not always easy to see the geological relation between the volcanic rocks and granitic rocks, then the exact radiometric age must be obtained on the volcanic rocks directly.

Thus, it has been urgently desired to determine the age of the late Mesozoic volcanic rocks in southwest Japan. The author carried out the Rb-Sr age determinations on volcanic rocks as well as the related granitic rocks. In this paper the results obtained are described and the geochronology and petrogenesis of the late Mesozoic igneous rocks of southwest Japan are discussed.

II Geological aspects

The late Mesozoic igneous rocks in the inner zone of southwest Japan are composed of both plutonic and volcanic rocks (Fig. 1). As a whole, these rocks are intermediate to acidic in composition and there are few basic rocks such as gabbro or basalt. This

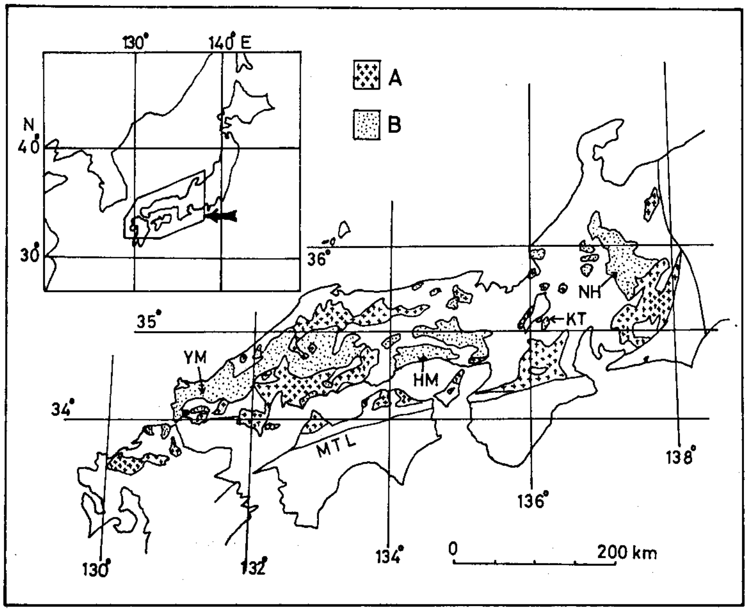


Fig. 1. Geological sketch map showing late Mesozoic-early Paleogene igneous rocks in southwest Japan (modified after RGLM, 1967). A: plutonic (granitic) rocks, B: volcanic rocks, YM: Yamaguchi district, HM: Himeji district, KT: Koto district, NH: Nohi district, MTL: Median Tectonic Line

phenomenon is one of the most distinctive features of the late Mesozoic igneous rocks of southwest Japan (RGLM, 1967, ICHIKAWA *et al.*, 1968).

The igneous rocks studied in the present investigation were collected from several areas, namely, Yamaguchi, Himeji, Koto and Nohi districts. In the next the brief comments on the geological aspects and the rock specimens used in this study are summarized. The sampling localities and geological maps are shown in Appendix-I.

A: Yamaguchi district

This district is the western end of the distributions of the upper Cretaceous volcanic rocks and has been investigated in detail by MURAKAMI and co-workers (MURAKAMI,

Table 1. Stratigraphical relations of igneous rocks of Yamaguchi district (after Murakami & Nishino, 1967; RGLM, 1967).

<table>
<tr><th>AGE</th><th>STAGE</th><th colspan="2">Southern part
(Setouchi-Sekiryo)</th><th colspan="2">Northern part
(San-in)</th></tr>
<tr><td rowspan="2">Paleogene</td><td>IV</td><td colspan="2" rowspan="2"></td><td>TAMAGAWA Group</td><td>P-IV Granite-Qz diorite
V-IV (Rhyolite)-Andesite</td></tr>
<tr><td></td><td colspan="2"></td></tr>
<tr><td rowspan="7">Upper Cretaceous</td><td>III</td><td colspan="4">P-III Granite-diorite, hypabyssal rocks</td></tr>
<tr><td rowspan="4">II</td><td>P-II</td><td colspan="3">Granodiorite, hypabyssal rocks</td></tr>
<tr><td rowspan="3">V-II
ABU Group</td><td>EFUNE Formation: Rhyolite -Andesite
500–800 m</td><td colspan="2"></td></tr>
<tr><td>MAIDANI Formation: Dacite
600–900 m</td><td colspan="2" rowspan="2">FUKUGA Formation: Rhyolite-(Andesite)
2000 m+</td></tr>
<tr><td>SHINOME Formation: Rhyolite-Andesite
300–500 m</td></tr>
<tr><td rowspan="2">I</td><td>P-I</td><td colspan="3">Qz. gabbro-granodiolite</td></tr>
<tr><td>V-I
SHUNAN Group</td><td>Rhyolite-Andesite
500-2000 m</td><td colspan="2">Rhyolite-Andesite</td></tr>
<tr><td>? Lower Cret.</td><td></td><td colspan="4">KWANMON Group</td></tr>
</table>

1960, 1969, 1974; NISHINO and MURAKAMI, 1965; MURAKAMI and NISHINO, 1967; MURAKAMI and MATSUSATO, 1970). Following geological aspects are reproduced from these papers.

The plutonic and volcanic rocks of this district ranging from upper Cretaceous to lower Tertialy are divided into four stages as shown in Table 1 (MURAKAMI and NISHINO, 1967; RGLM, 1967). The volcanic rocks of Stage-I are denoted V-I and plutonic rocks as P-I, and similarly for other Stages. The main volcanic activity corresponds to Stage-II (Abu group) and main plutonic one to Stage-III.

The Shunan group (V-I) consists of andesitic to rhyolitic rocks which distribute in several elongated cauldron areas. The Abu group (V-II) unconformably overlying the Shunan group distributes in the northern half of Yamaguchi Prefecture. This group consists of rhyolitic to rhyodacitic welded tuff with a little amount of andesitic rocks. The granitic rocks (P-III), which are correlated to the Hiroshima granite of central Chugoku district, are intruded mainly in the southern part of Setouchi area. Small granitic bodies crop out in the coastal area of Japan Sea, too. The Tamagawa group (V-IV, P-IV) is distributed in a elliptical cauldron area surrounded by Paleozoic basements and Fukuga formation of the Abu group (MURAKAMI, 1969, 1973).

Samples studied are as follows.

YM04, 08 and 09: Rhyolitic welded tuff (Shinome formation of the Abu group)

YM06: Andesitic welded tuff (Shinome formation of the Abu group)

YM18: Granitic rock. This rock was believed to be closely connected with the Tamagawa group (MURAKAMI, 1969). Detailed discussion will be given later in this paper.

YM23: Granite (P-III)

YM27: Diorite (P-III)

TM01: Biotite granite of the Tamagawa group (Same locality as No. 17 in Table 3 in MURAKAMI, 1969)

B: Himeji district

The volcanic and plutonic rocks of the late Mesozoic age in the Himeji district, southwestern part of Hyogo Prefecture, were investigated mainly by KISHIDA and WADATSUMI (1967). The next geological aspects are given following them.

The late Mesozoic igneous rocks, collectively named "Himeji acid volcano-plutonic complex", distribute mainly in Himeji area in the east and Aioi, Akoh and Kamigori area in the west. The samples studied in this paper were collected from the latter area. The Himeji acid volcano-plutonic complex is divided stratigraphically into the Hiromine group, Aioi group, Harima granite and Tenkadaiyama group from lower to upper as shown in Table 2. The Hiromine group, which comprises rhyolitic tuff, breccia and shale, does not distribute in the western part of this district and therefore this group is not included in Table 2.

The main volcanic activity resulted in the formation of the Aioi group. This

Table 2. Stratigraphical relations of igneous rocks in the western Himeji district (after Kishida & Wadatsumi, 1967).

<table>
<tr><th>AGE</th><th colspan="3">Western part of Himeji district (Aioi, Akoh and Kamigori areas)</th></tr>
<tr><td>Paleo-gene ?</td><td rowspan="5">Himeji acid volcano-pultonic complex</td><td colspan="2">TENKADAIYAMA Group: Rhyolite lava flow</td></tr>
<tr><td rowspan="4">Upper Cretaceous</td><td colspan="2">HARIMA Granite: Granite porphyry-granophyre</td></tr>
<tr><td rowspan="3">AIOI Group</td><td>AKOH Formation: Rhyolite</td></tr>
<tr><td>TSURUKAME Formation: Rhyodacite-andesite</td></tr>
<tr><td>KAMIGORI Fomation: Rhyolite, shale, breccia</td></tr>
</table>

group is subdivided into three formations, Kamigori, Tsurukame and Akoh formations, in ascending order. These formations mainly consist of rhyolitic-andesitic welded tuff (SiO_2=57–77%).

The Harima granite intrudes into the volcanic rocks of the Aioi group and gives the contact metamorphic effect to them. Almost all of the Harima granite show the porphyritic texture. Silica contents are ranging from 58% to 74%.

Samples studied are as follows.

HM01, 02, 03 and 06: Rhyolite lava (Tenkadaiyama group)
HM07, 09 and 11: Porphyritic granite (Harima granite)
HM14: Dacite (Tsurukame formation of the Aioi group)
HM15: Andesite (ditto)
HM17: Rhyolite (Hattoji rhyolite in Akoh formation of the Aioi group)
HM21: Rhyolitic tuff breccia (Kamigori formation of the Aioi group)
HM22: Rhyolitic welded tuff (Akoh formation of the Aioi group)

C: Koto district

"Koto" means the east side of the Lake Biwa. The acidic rocks of the late Mesozoic age in this area had been considered to be hypabyssal rocks and called quartz porphyry for long years (e.g. GEOLOGICAL SURVEY OF JAPAN, 1895; TATEKAWA *et al.*, 1967), but they were recognized to be volcanic products and renamed "Koto welded tuff" by KAWADA (1969). This improved study filled to some extent the gap of the distributions of the volcanic rocks from "Arima group" in Hyogo Prefecture to "Nohi rhyolite" in the Chubu district.

The distribution of Koto welded tuff is limited in the small area at the present time, but it is supposed that the volcanic rocks had been distributed in larger area in the past time (KAWADA, 1969). From this supposition the total volume is estimated

Table 3. Stratigraphical relations of igneous rocks of Koto district (after Kawada, 1969; Mimura, 1975).

	Succession		Rock type
	Intrusive rocks		Quartz porphyry-Granite porphyry
KOTO RHYOLITE	KOTO-III	220 m	Rhyolitic welded tuff
	KOTO-II	90 m	Rhyolitic welded tuff
	Sedimentary rocks		Breccia, sandstone, mudstone
	Instrusive rocks		Granodiorite porphyry
	KOTO-I	200 m	Rhyodacitic welded tuff

to be more than 10^3 km^3 (MIMURA, 1971). MIMURA (1975) summarized the petrography of these rocks and divided them into three types, namely, Koto-I, II and III from lower to upper. The rock type and distribution area of Koto-II and III are almost the same. Porphylitic dyke rocks intrude into both Koto-I and Koto-II, III (Table 3). The volcanic rocks of Koto-I are rhyolitic-rhyodacitic welded tuff (SiO_2= 70–75%) and those of Koto-II and Koto-III are rhyolitic welded tuff (SiO_2=75–78%) (MIMURA, 1975).

Samples studied are as follows.

KT01, 03, 09, 10 and 11: Rhyodacitic welded tuff (Koto-I)
KT06 and 25: Granodiorite porphyry which intrudes into Koto-I.
KT08, 42, 43 and 45: Rhyolitic welded tuff (Koto-II)
KT32, 40 and 41: Rhyolitic welded tuff (Koto-III)

D: Nohi district

The acid volcanic rocks distributed in the Chubu district were named as a whole "Nohi Rhyolite" (KAWADA *et al.*, 1961). The total volume of the volcanic rocks is estimated to be about 10^4 km^3 or more (YAMADA *et al.*, 1971). Most part of the "Nohi Rhyolite" is composed of pyroclastic flows which deposited on the land surface. These rocks show welded flow structure, ranging from andesitic to rhyolitic in composition (SiO_2=58–76%).

The volcanic activity is divided stratigraphically into five stages which are named Stage-I, II and so on from lower to upper (Table 4). All of Stage-I–IV, however, are called collectively "Nohi Rhyolite" and the time of formation is presumed to be between 80 m.y. and 100 m.y. (YAMADA *et al.*, 1971). The granitic rocks in the

Table 4. Stratigraphical relations of Nohi rhyolite. Modified after the data of Yamada, Kawada and Morohashi (1971), CRGNR (1973), and Okamoto (1973). The names of successions are not listed except for what are used in this paper. Shaded areas are sedimentary rocks.

Stage	Southern part	Eastern part	Western part
V		Rhyolitic welded tuff	
IV		Rhyodacitic welded tuff	
III		UGUIGAWA F. MAYUMITOGE F. TAKATARU F. } rhy. wel. tuff ATERA F.	
II		YUMORIYAMA F. AKAISHI F. HIGASHIMATA F.	rhyodacitic wel. tuff rhyolitic welded tuff // MARUYAMA F.
I	Rhyolitic-rhyodacitic welded tuff		SHIMOSAMI F. AKO F. } rhy. wel. tuff

Ryoke metamorphic belt of the Chubu district were divided into two groups, namely older granite and younger granite, besed on their geological relations to the "Nohi Rhyolite" (RGRB*, 1972).

The volcanic rocks of Stage-I distribute in the southern and western marginal parts of the mass. Samples studied were collected from the western marginal part where was surveyed by KAWADA (1971) and OKAMOTO (1973). All samples, which are ranging from dacite to rhyolite, belong to Ako formation of Stage-I.

III Analytical procedures

A: Sampling

Rock specimen, about 5 kg, was collected from the outcrop of typical locality. About 3 kg of fresh rock specimen was broken down and prepared for whole rock samples and for mineral separations. Mineral separations were performed by using a Frantz isodynamic separator and heavy liquids.

Almost all volcanic rocks determined in the present study are welded tuff. It is difficult to obtain the pure mineral except for quartz, plagioclase and K-feldspar of large phenocrysts. Therefore in some cases, groundmass of rock was used for drawing internal isochron. The detailed description of the separation is shown in Appendix-II.

* RGRB=Research group for the Ryoke belt.

B: X-ray fluorescence

To obtain optimum spiking ratio for both rubidium and strontium, it is necessary to know the approximate amount of Rb and Sr content. This was achieved by X-ray fluorescence method. In the course of the present study, rapid but rough measurement was achieved on most samples by applying to X-ray as powdered state. In general case, Rb/Sr ratio was obtained within the error of 10%. For some specimens, Rb and Sr contents were obtained from the application of pressed pellets (SEKI, 1971) with the maximum error of 5%.

C: Mass spectrometric determination

Rubidium and strontium analyses were carried out on two mass spectrometers. One is a 9 inch radius 60° sector solid source mass spectrometer, Mitsubishi Model 223, which is set at geochronological laboratory of Kyoto University. Rubidium and strontium were run on single Ta filament. Strontium isotopic ratios were calculated from 20–30 sets on the strip chart.

The other one is 30 cm radius 90° sector solid source mass spectrometer, JEOL Model 05RB, of Kyushu University. Strontium samples were loaded on the center filament of triple Ta filaments assembly. Thirty to sixty sets of Sr isotopic ratios were obtained from a digital voltometer, Takeda Riken Model TR6515.

The error of Sr^{87}/Sr^{86} of one analysis is generally within 0.15% by Kyoto machine and 0.08% by Kyushu machine, respectively. All Sr^{87}/Sr^{86} ratios are normalized to 0.7080 of Eimer & Amend $SrCO_3$. The maximum error of 2% is assigned to the Rb^{87}/Sr^{86} ratio. Contribution of Rb^{87} to Sr^{87} peak during a mass spectrometer run was negligible for all samples and no corrections for blanks were made for either Rb or Sr.

D: Constants used

Rubidium concentrations are calculated using the atomic abundance of Rb^{87} to be 27.85%. The isotopic ratios for normal Sr used are $Sr^{86}/Sr^{88}=0.1194$ and $Sr^{84}/Sr^{88}=0.0068$ and all Sr results have been normalized to $Sr^{86}/Sr^{88}=0.1194$.

The calculations of a best fit isochron through the data points are followed the treatment of York (1966). The stated errors of age and initial Sr ratio are $\pm 2\sigma$. In all calculations of Rb-Sr ages the value of 1.42×10^{-11}/year (NEUMANN and HUSTER, 1976) is used for the decay constant of Rb^{87}.

IV Results and discussions

A: Geochronology

A-1, Yamaguchi district

All results for this district are shown in Table 5.

1) TM01

The age of TM01 is 39.3 ± 4.6 m.y. which is calculated from tie line of biotite

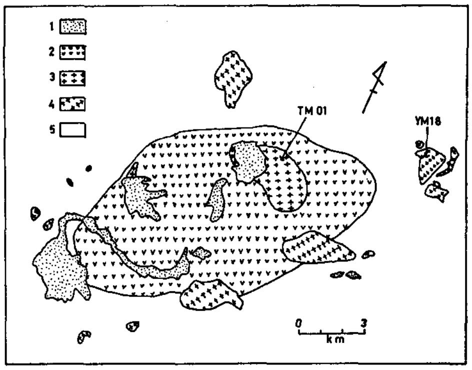


Fig. 2. Generalized geological map of the Tamagawa Cauldron area and sampling localities. (simplified after Murakami, 1973)
1: Quaternary basaltic rocks, 2: volvanic rocks of the Tamagawa group, 3: granite, 4: diorite or garnodiorite, 5: basement rocks

and K-feldspar (Fig. 3). The geological age of the Tamagawa group was presumed to be Oligocene or Eocene based on a K-Ar age* of the correlative granitic rock and on the field evidences (RGLM, 1967; MURAKAMI, 1969), although there were no determinations for the rocks in the Tamagawa cauldron. The granitic rock of TM01 was collected from the locality in this cauldron (Fig. 2), so the age of TM01 is the first

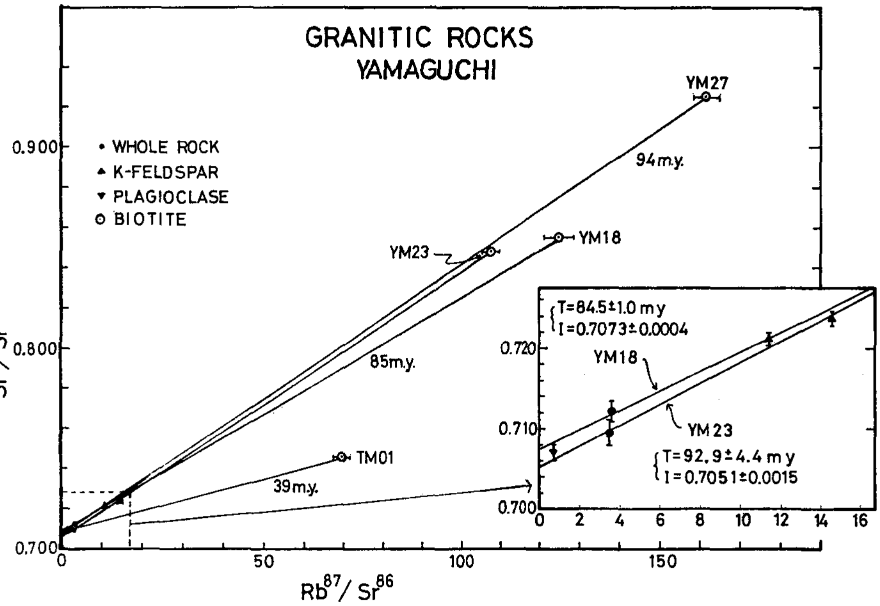


Fig. 3. Rb-Sr evolution diagram for granitic rocks of Yamaguchi district. Whole rock and feldspar data of YM18 and YM23 are shown in the insert.

* A K-Ar determination gives an age of 36 m.y. for the granitic rock which intrudes into the formation correlated to the Tamagawa group at Kannonzaki, Misumi Cho of Shimane Prefecture (Kawano and Ueda, 1966).

data for the Tamagawa group. This age is consistent with the estimation stated above. Therefore the age of the Tamagawa group is considered to be about 39 m.y., i.e., late Eocene.

2) YM18

Rubidium and strontium analyses were made for YM18 on its whole rock, K-feldspar and biotite. The best fit isochron yields an age of 84.5±1.0 m.y. and an initial Sr^{87}/Sr^{86} ratio (IR) of 0.7073±0.0004 (Fig. 3).

The rock specimen of YM18 was collected from a granitic body which locates 2 km apart from the Tamagawa cauldron (Fig. 2), and this small rock body has been considered to be related to the Tamagawa group (e.g. Murakami, 1973). However, the isochron age of YM18 is twice as old as the age of the Tamagawa group. In general, the internal isochron drawn through mineral fractions gives the same or younger age and not an older age of the emplacement of the rocks. From the view point of this, the granitic body of YM18 is considered to be related to the Cretaceous granite, which distributes widely in the inner zone of southwest Japan, rather than to the Tamagawa group. Consequently it seems to be necessary to reexamine whether

Table 5. Analytical results: Yamaguchi district

Sample	Rb (ppm)	Sr (ppm)	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
GRANITIC ROCKS				
TM01WR*	30.73	222.9	0.399	
Kf	102.3	274.7	1.079	0.7079±13‡
Bi	336.9	14.08	69.54	0.7462±18
YM18WR	143.7	116.0	3.588	0.7119±13
Kf	408.6	105.2	11.40	0.7209± 8
Bi	961.5	22.65	124.7	0.8571±11
YM23WR	134.1	112.2	3.461	0.7093±16
Pl	21.60	121.3	0.515	0.7069±11
Kf	418.6	83.41	14.57	0.7235± 9
Bi	338.2	9.26	107.6	0.8479±15
YM27WR	78.80	284.3	0.803	0.7084± 9
Bi	451.8	8.27	161.7	0.9248±10
ABU GROUP				
YM04WR	240.3	159.2	4.371	0.7122± 5†
YM06WR	84.71	225.5	1.088	0.7070± 6†
YM08WR	150.4	241.7	1.802	0.7080± 7†
YM09WR	172.3	173.5	2.877	0.7098± 4†

*: WR; whole rock, Kf; K-feldspar, Pl; plagioclase, Bi; biotite
‡: error $\pm 1\sigma (\times 10^4)$
†: analized by Kyushu machine

some small satellitic granitic bodies surrounding the cauldron (Fig. 2) are related to the Tamagawa group or not.

3) YM23

The internal isochron of YM23 drawn through the data points of whole rock, K-feldspar, biotite and plagioclase yields an age 92.9±4.4 m.y. and IR=0.7051±0.0015 (Fig. 3). This isochron age is concordant to the K-Ar age of 91 m.y. from the same rock body (Kawano and Ueda, 1966). Therefore this age is considered to indicate the time of the granitic intrusion. Because this granitic body intrudes into Fukuga formation of the Abu group, the age of Fukuga formation should be older than 93 m.y.

Recently Shibata and Kamitani (1974) carried out some K-Ar determinations on the muscovite specimens collected from the "Roseki" mine which deposited in the Fukuga formation, and the age of about 82 m.y. was obtained. They also obtained a muscovite age of 79 m.y. on the pegmatite which intrudes into the Fukuga formation. From these data they considered that the "Roseki" deposits had been formed in close connections with the granite intrusion about 80 m.y. Considering the data of YM18 and YM23 discussed above, it follows that the Fukuga formation was formed at some time older than 90 m.y. and some part of the formation was hydrothermally altered to form the "Roseki" deposits by the intrusion of the granitic rocks of about 80 m.y.

4) YM27

The age of YM27 given by the tie line of biotite-whole-rock is 94±4 m.y. (Fig. 3). This is same to the age of YM23, though the localities of these specimens are not near; YM23 is in Japan Sea side and YM27 is in Setouchi area (Appendix-I). Judging

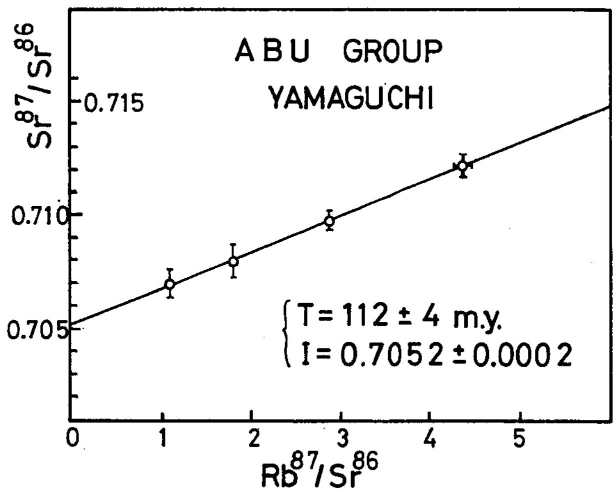


Fig. 4. Rb-Sr evolution diagram for the volcanic rocks of the Abu group.

from most K-Ar ages of the Hiroshima granite (P-III) in Yamaguchi Prefecture to be 80–95 m.y. (KAWANO and UEDA, 1966), it may be stated that the ages of YM23 and YM27 represent the first stage of the emplacement of the Hiroshima granite.

5) Abu group

The data of volcanic rocks of the Abu group are plotted in Rb-Sr evolution diagram of Fig. 4. The whole rock isochron yields an age 112 ± 4 m.y. and IR=0.7052 ± 0.0002.

This age bears a primary importance to the volcanic history of the Yamaguchi district. The fact that the isochron indicates the age of the Abu group to be close to 110 m.y. offers a significant limitation on the age of the Kwanmon group which underlies the Abu group; that is, the age of the Kwanmon group should be older than 110 m.y. This implies that the age of the Kwanmon group is limited in Neocomian (136–112 m.y.) and not in Neocomian-Albian (136–100 m.y.; RGLM, 1967; MATSUMOTO, 1967). Therefore the reexamination on the geological relations and fossils of the Kwanmon group, which were used for deciding the age of this group previously, is desired.

A-2 Himeji district

The results of the samples from this district are listed in Table 6.

1) Tenkadaiyama group

For the Tenkadaiyama group, four whole rocks and four fractions separated from HM06 were analyzed. All of these eight data points are arranged on a straight line which defines an age 69.9 ± 4.3 m.y. and IR=0.7103 ± 0.0004, as illustrated in Fig. 5.

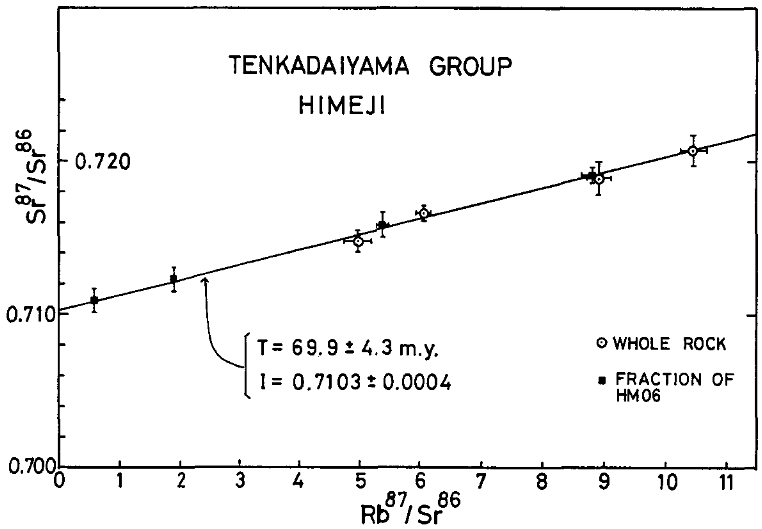


Fig. 5. Rb-Sr evolution diagram for the Tenkadaiyama group.

Table 6. Analytical results: Himeji district

Sample	Rb (ppm)	Sr (ppm)	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
TENKADAIYAMA GROUP				
HM01WR*	169.5	98.8**	4.968	0.7148± 7‡
HM02WR	247.0	68.44	10.46	0.7207±10
HM03WR	221.7	71.97	8.929	0.7189±11
HM06WR	188.9	89.93	6.086	0.7166± 5
Fr-1	198.9	65.25	8.837	0.7191± 5
Fr-2	213.9	114.7	5.404	0.7158± 9
Fr-3	62.45	283.0	0.639	0.7109± 8
Fr-4	132.1	203.7	1.879	0.7123± 8
HARIMA GRANITE				
HM07WR	109.3	103.4	3.062	0.7097±10
Kf	264.5	86.94	8.805	0.7158± 8
HM09WR	110.2	236.6	1.348	0.7072±10
Pl	19.05	440.3	0.125	0.7056±10
Ho	8.373	82.29	0.295	0.7064± 7
Kf	266.8	119.7	6.455	0.7130± 6
HM11WR	97.7**	159**	1.778	0.7073± 9
AIOI GROUP				
HM14WR	83.0**	271**	0.887	0.7063±13
HM15WR	20.6**	427**	0.140	0.7059± 9
HM17WR	154**	68.9**	6.476	0.7161±10
Pl+Qz	13.56	10.83	3.629	0.7140±10
Kf	371.9	55.75	19.35	0.7302± 9
HM21WR	135.1	86.32	4.529	0.7125± 6†
Pl	50.25	175.7	0.828	0.7082± 7†
Kf	374.1	127.2	7.908	0.7155± 7†
Pm	258.6	85.64	8.751	0.7165± 5†
M4	159.2	74.17	6.219	0.7150± 7†
HM22WR	174.6	203.6	2.483	0.7093±10

* : WR; whole rock, Kf; K-feldspar, Pl; plagioclase, Ho; hornblende, Other simblos are shown in Appendix-II.
** : by X-ray fluorescence
‡ : error $\pm 1\sigma (\times 10^4)$
† : analized by Kyushu machine

This isochron age is the first isotopic age datum for this group. Because the whole rock specimens and separated fractions are both lying concordantly on a single straight line, it is recognized that the Rb-Sr system has not been opened since its formation. Consequently it is concluded that the time of the Tenkadaiyama group is indicated by the isochron age, that is, uppermost Cretaceous.

2) Harima granite

Three whole rocks, two K-feldspars, one plagioclase and one hornblende were obtainable for determinations from the Harima granite. All points of these data define a straight line well within the assigned errors (Fig. 6). The age obtained is 79.7± 5.5 m.y. and IR=0.7058±0.0004.

Judging from the isochron plots, the Rb-Sr system of the Harima granite seems to have been kept in closed system since its formation. Therefore the isochron age is considered to indicate the time of intrusion. The very concordant K-Ar age of 79 m.y. on biotite (# G-334, KAWANO and UEDA, 1966) from same locality of HM09 supports this interpretation.

To the northeast of the Himeji acid volcano-plutonic complex, the Ikuno group which is composed of the acid-intermediate volcanic rocks distributes widely. Some K-Ar age determinations were carried out in order to decide the time of the ore deposition of Ikuno mine in the Ikuno group (ISHIHARA and SHIBATA, 1972). From these determinations the age of pre-ore rhyolite was obtained to be 72.8±2.9 m.y. It is noteworthy that this age is concordant with the age of the Tenkadaiyama group within the assigned errors. On the other hand, IMAI *et al.* (1970) reported the K-Ar age of 77 m.y. for the biotite of granitic rock which intrudes into the Ikuno group. This age agrees to that of the Harima granite. Judging from the concordancies of the ages for both granitic rocks and rhyolitic rocks, the formation of the Ikuno group seems to be closely related to the Himeji acid volcano-plutonic complex.

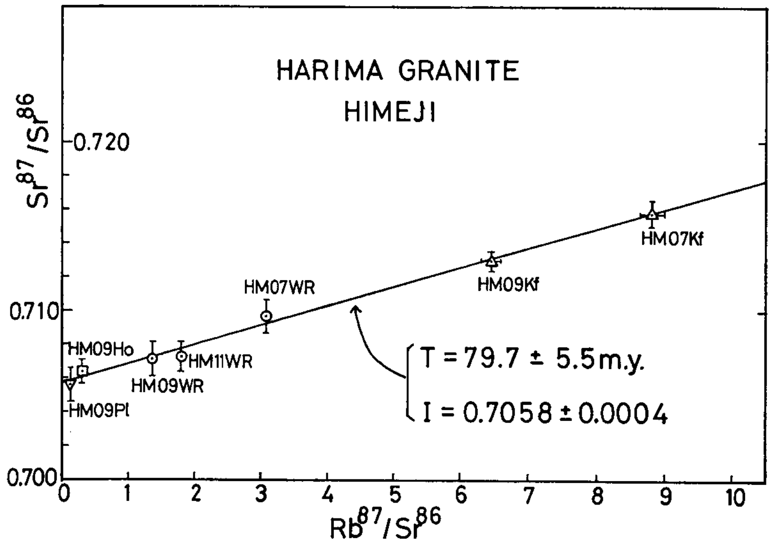


Fig. 6. Rb-Sr evolution diagram for the Harima granite.

3) Aioi group

The determinations were made on five whole rocks and two fractions of HM17 and four fractions of HM21 from the Aioi group. Differing from the case of the Tenkadaiyama group or the Harima granite, these data points of the Aioi group do not lie on a single straight line. The data of whole rocks and those of separated fractions show the different isochrons as shown in Fig. 7. The whole rock isochron (solid line in Fig. 7) indicates an age 118±12 m.y. and IR=0.7052±0.0007. On the other hand, four fractions and whole rock of HM21 define an internal isochron which yields a younger age of 73±13 m.y. and IR=0.7077±0.0012 (lower dashed line in Fig. 7), and similarly two fractions and whole rock of HM17 are arranging on an isochron of an age 74±8 m.y. and IR=0.7098±0.0013 (upper dashed line in Fig. 7).

This fact indicates that the Rb-Sr system of the volcanic rocks of the Aioi group has been opened at least once since the time of its formation, which is represented by the whole rock isochron. Because the internal isochron of both HM17 and HM21 yield about 70 m.y., the final isotopic re-homogenization within the mineral facies seems to have occurred at about 70 m.y. ago. This age is almost identical with that of the Tenkadaiyama group. Therefore, it is possible that the isotopic re-homogenization was caused by the volcanic activity of the Tenkadaiyama group.

Some K-Ar ages have been reported on the volcanic rocks of the Aioi group (RGLM, 1967; Kono, Ozima and Wadatsumi, 1974). All results, however, are younger than 73 m.y. Kono *et al.* concluded from their determinations that the age of the

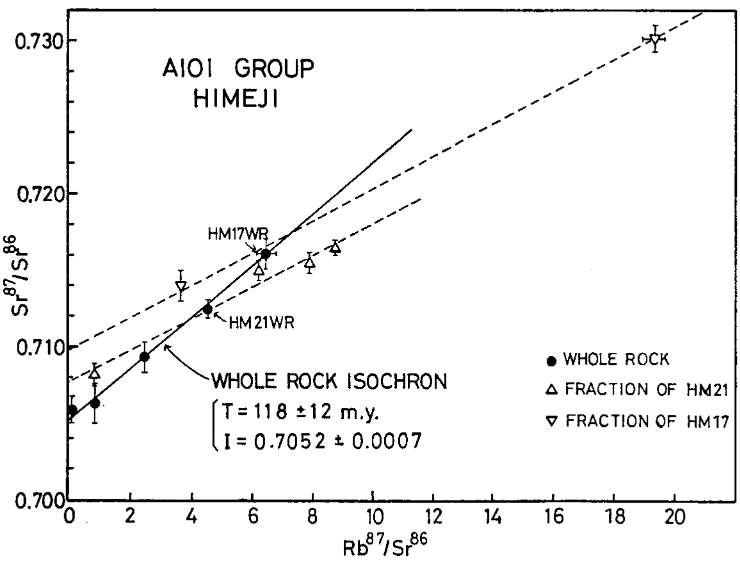


Fig. 7. Rb-Sr evolution diagram for the Aioi group. Whole rock isochron is shown by a solid line. Two internal isochrons for HM17 and HM21 are shown by dashed lines.

Aioi group is 70 ± 3 m.y., but this conclusion seems to be misunderstanding from the view point of the present study. The reason is that the age of the Aioi group must be older than that of the Harima granite (about 80 m.y.), because the Aioi group is intruded by this granite. Consequently it is reasonably considered that the K-Ar ages of the Aioi group does not represent the time of eruption but re-homogenized age. This is the same case as the internal isochron ages of HM17 and HM21. Therefore both of K-Ar and internal isochron ages might be resulted from the volcanic activity of the Tenkadaiyama group.

In Mitsuishi area of the western extention of the Himeji acid volcano-plutonic complex, there are also distributed the acid volcanic rocks of the late Mesozoic era. These volcanic rocks, which comprise rhyolitic welded tuff with minor amount of andesitic welded tuff, are considered to be correlative with the Aioi group (SHIBATA and FUJII, 1971). In this area there are the "Roseki" deposits which are considered to be formed from rhyolitic welded tuff by the alteration of strong acidic hydrothermal activity. Two possibilities have been proposed regarding the time of the formation of the "Roseki" deposit of this area. One is the time of the eruption of the host volcanic rocks (e.g. KINOSHITA, 1963) and the other is the time of the Paleogene volcanism such as the Tenkadaiyama group (SHIBATA *et al.*, 1967). To decide this problem, SHIBATA and FUJII (1971) carried out a K-Ar age determination on the sericite mineral that had been formed at the same time of the "Roseki" deposits and obtained an age of 78.7 ± 3.2 m.y. This age is younger than that of the Aioi group and older than the Tenkadaiyama group. Therefore it can be said that both of two possible opinions on the time of the formation of the "Roseki" deposits at Mitsuishi area are not suitable. On this problem the present author would like to point out that the K-Ar age of 78.7 ± 3.2 m.y. agrees very well with the isochron age of the Harima granite (79.9 ± 5.5 m.y.). Hence, it is considered that the hydrothermal activity which formed the "Roseki" deposits at Mitsuishi area was caused by the intrusion of the granite. This is analogous to the fact observed in Yamaguchi prefecture where the intrusion of granitic rocks caused the "Roseki" deposits (KAMITANI, 1974; SHIBATA and KAMITANI, 1974). Consequently it is likely that the "Roseki" deposits of southwest Japan were formed by the intrusion of the granitic rocks.

From the paleomagnetic investigations, SASAJIMA and SHIMADA (1966) discovered that the volcanic rocks of the Akoh formation in the Aioi group revealed the reversed polarity. Because there are very few reversed polarity data in the middle-upper Cretaceous, this datum has been referred as an unique reversed polarity, for which MCELHINNY and BUREK (1971) proposed to be named "Akoh zone". There has been confusion, however, on the age of the Akoh formation, because of a few age determination (e.g. VAN HINTE, 1976). The whole rock isochron age of the Aioi group (118 ± 12 m.y.) may offer a solution, because the Akoh formation is one of the members of the Aioi group. This age is close to that of the Abu group (112 ± 4 m.y.) or the Nohi rhyolite Stage-I (105±8 m.y.) obtained in this study. This indicates that the volcanic activity occurred synchronously at about 110 m.y. ago in the southwest Japan. Consequently the reversed polarity of "Akoh zone" may correspond to the "Hissar zone" (McELHINNY and BUREK, 1971), which is placed near 110 m.y. BP.

A-3 Koto district

The analytical results are listed in Table 7.

1) Koto-II, III

The samples belonging to Koto-II were analyzed on four whole rocks as well as plagioclase and K-feldspar separated from KT08. All data construct an isochron of an age 75.8±2.4 m.y. and IR=0.7095±0.0009. On the contrary, the data of the whole rock specimens of Koto-III do not define a straight line as shown in Fig. 8.

Table 7. Analytical results: Koto district

Sample	Rb (ppm)	Sr (ppm)	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
KOTO-III				
KT32WR*	287.5	19.01	43.96	0.7533±10♯
KT40WR	221.2	18.06	35.64	0.7558±13
KT41WR	247.0	27.16	26.40	0.7370±15
KOTO-II				
KT08WR	205.1	60.99	9.750	0.7202±10
Pl	7.14	65.50	0.316	0.7104±13
Kf	379.7	92.75	11.86	0.7221±12
KT42WR	252.2	26.80	27.33	0.7381± 7
KT43WR	226.0	27.84	23.56	0.7351±11
KT45WR	434.4	18.35	69.02	0.7847±10
INTRUSIVE ROCKS				
KT06WR	118.5	223.2	1.537	0.7122±14
KT25WR	141.7	121.7	3.374	0.7157±14
KOTO-I				
KT01WR	122.7	118.0	3.102	0.7135±12
KT03WR	125.0	113.9	3.179	0.7154± 8
KT09WR	140.2	105.9	3.835	0.7165± 7†
Fd-D	203.9	97.65	6.053	0.7183± 7†
-200 m	131.0	135.8	2.795	0.7148± 7†
F-1	151.5	91.86	4.778	0.7161± 9†
F-2	186.6	87.22	6.202	0.7183± 6†
KT10WR	114.9	193.4	1.721	0.7121± 6
KT11WR	64.83	326.9	0.5744	0.7110± 9

* : WR; whole rock, Pl; plagioclase; Kf; K-feldspar, Other simbols are shown in Appendix-II.
♯ : error $\pm 1\sigma (\times 10^4)$
† : analized by Kyushu machine

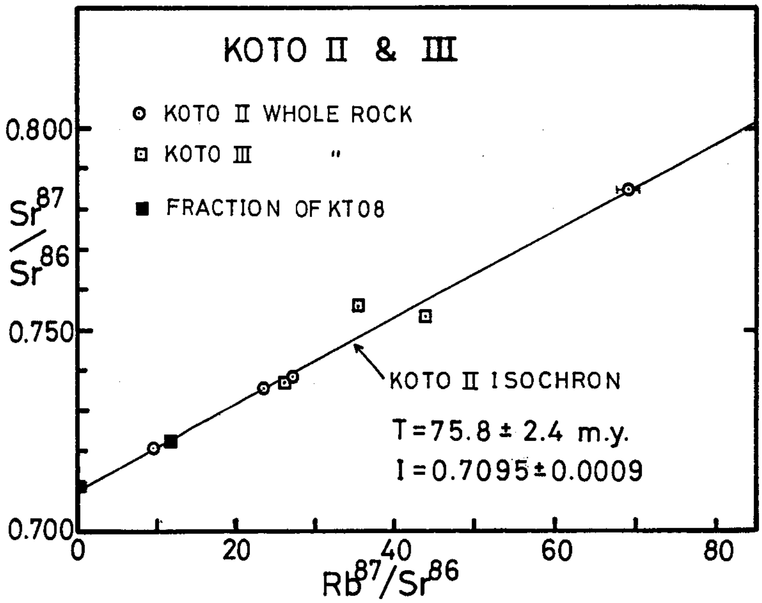


Fig. 8. Rb-Sr evolution diagram for KOTO-II and III. The isochron is drawn through data points of KOTO-II.

The volcanic rocks of Koto-II and III reveal a characteristic feature on the concentrations of Rb and Sr, that is, high Rb and low Sr contents. Consequently the Rb/Sr ratio is very high. Especially the Rb/Sr ratio of KT45 (=23.67) represents the highest value in all late Mesozoic igneous rocks of southwest Japan.

Many mineral ages have been reported on the granitic rocks around the Lake Biwa (ALDRICH *et al.*, 1962; KAWANO and UEDA, 1966; HAYASE and ISHIZAKA, 1967; YAGI *et al.*, 1968). The reliable data for biotite ages are picked up from these numerous data and shown in Fig. 9. From this figure, the data seem to be separated into two groups, about 75 m.y. and 95 m.y. The former consists mainly of the data of Mt. Tanakami to the south of the Lake Biwa and the latter age group of the data of Mts. Hiei and Hira to the west of the Lake Biwa.

The isochron age of Koto-II is close to the age of the younger granitic rocks in Fig. 9. The granitic rocks of Mt. Tanakami are known to be very acidic in com-

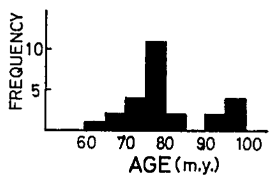


Fig. 9. Frequency of biotite ages of granitic rocks around the Lake Biwa.

position, and the same chemical character is also indicated for the volcanic rocks of Koto-II, as shown above. These characteristics on age and chemical composition seem to indicate that the volcanic rocks of Koto-II and the granitic rocks of Mt. Tanakami are in co-magmatic relation.

2) Koto-I

The data for the volcanic rocks of Koto-I are shown in the Rb-Sr evolution diagram of Fig. 10. The whole rock isochron (solid line in Fig. 10) yields an age 121 ± 35 m.y. and IR$=0.7096\pm0.0014$. On the other hand, the internal isochron of KT09 (dashed line in Fig. 10) yields an age 69 ± 23 m.y. and IR$=0.7122\pm0.0012$. This age is younger than whole rock isochron age, and the same phenomenon has been recognized on the volcanic rocks of the Aioi group.

Although the isochron age of Koto-I has a large analytical error, it can be stated that the age of Koto-I is same or older than the older granitic rocks of about 95 m.y. shown in Fig. 9.

Two data of the intrusive rocks (KT06 and KT25) are located on the whole rock isochron of Koto-I (Fig. 10). This may be interpreted as that the intrusive rocks have same age and same initial Sr^{87}/Sr^{86} ratio as those of Koto-I within the stated errors.

A-4 Nohi district

Five whole rock specimens were analyzed for the volcanic rocks of Nohi district. The data well define an isochron which yields an age 105 ± 8 m.y. and IR$=0.7078\pm0.0011$ (Table 8, Fig. 11).

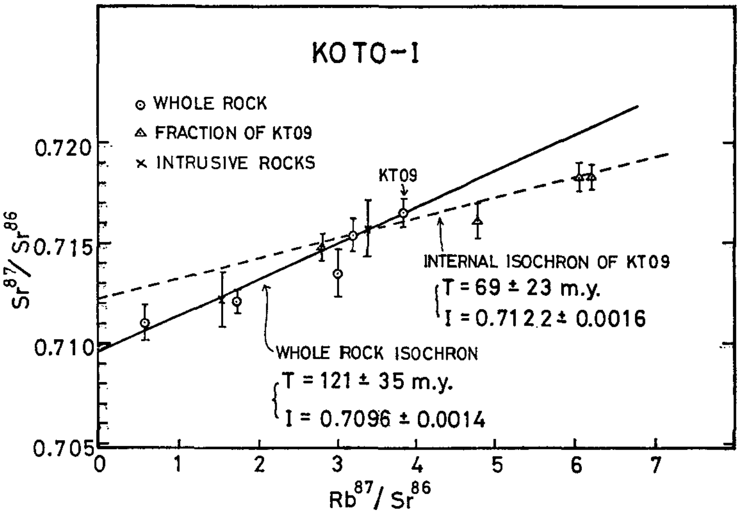


Fig. 10. Rb-Sr evolution diagram for KOTO-I. The internal isochron for KT09 is shown by a dashed line.

Table 8. Analytical results: Nohi rhyolite Stage-I

Sample	Rb (ppm)	Sr (ppm)	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
NH01WR	235.5	166.7	4.093	0.7136±10*
NH02WR	245.9	71.00	10.04	0.7239±15
NH03WR	261.0	67.95	11.14	0.7240± 8
NH04WR	271.5	50.20	15.68	0.7315± 8
NH05WR	128.5	214.6	1.734	0.7108±11

* : error $\pm 1\sigma (\times 10^4)$

This well-defined isochron is considered to indicate the time of eruption. This age, however, does not indicate the age of the whole "Nohi rhyolite" but only the age of Stage-I. OKAMOTO *et al.* (1975) showed that the whole rock isochron age of Stage-II was about 75 m.y. The time gap between Stage-I and Stage-II is, indeed, 30 m.y. Therefore, the time range of the whole "Nohi rhyolite" (Stage-I–V) becomes much more than 30 m.y. This is not compatible with the previous suggestion that the "Nohi Rhyolite" was formed during the period from 100 m.y. to 80 m.y. (YAMADA, KAWADA and MOROHASHI, 1971). Therefore, the age relation between "Nohi Rhyolite" and

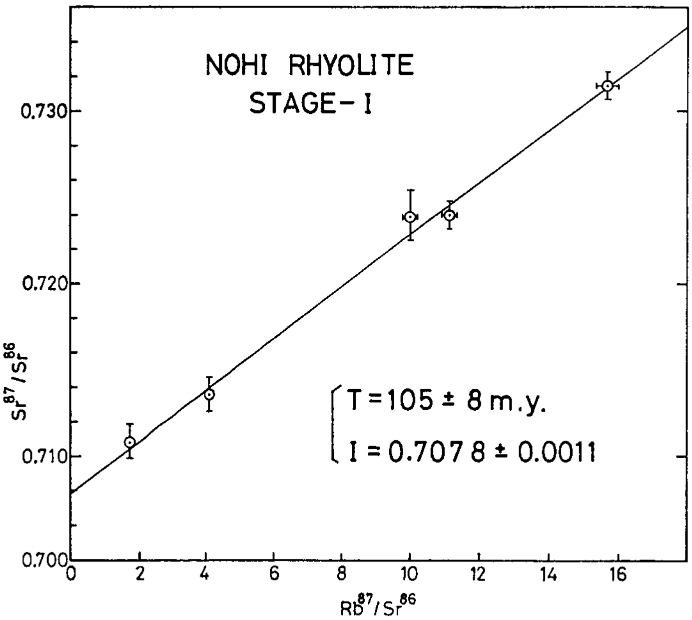


Fig. 11. Rb-Sr evolution diagram for Nohi rhyolite, Stage-I.

granitic rocks of the Chubu district (RGRB, 1972) must be misleading and need to be rewritten.

The present author tries to construct a new correlative time table between volcanic rocks and granitic rocks of the Chubu district in Table 9. In this table, the age of "Nohi Rhyolite" are divided into three groups, namely Stage-I, Stage-II–IV and Stage-V, because Stage-V is considered to have erupted with some significant time gap after Stage-IV (CRGNR*, 1973). Therefore, the age of Stage-V is shown in this table to be about 60 m.y. which is the same age as Shirakawa granite (HAYASE and ISHIZAKA, 1967; SHIBATA, SASAKI and KAWADA, 1971).

B: Space-time relations

B-1 Volume of igneous rocks

The first trial to estimate the volume of the late Mesozoic volcanic rocks in the inner zone of southwest Japan was done by RGLM (1967). Here the author re-estimates the volume of volcanic rocks on the basis of the results of RGLM, taking into account of the age data obtained in the present study and of some new geological informations (KAWADA, 1969; YAMADA *et al.*, 1971; MURAKAMI, personal com.). The volume of granitic rocks is newly estimated in the present study and compared with that of volcanic rocks.

The amounts of volcanic rocks are estimated from [distribution area × average thickness] and the volume of granitic rocks are from [distribution area × thickness (5 km)]. All results are summarized in Table 10.

From Table 10, it can be seen that the volcanic rocks of about 9×10^4 km^3 and granitic rocks of about 1.6×10^5 km^3 were formed throughout the late Mesozoic era. On the average, the igneous rocks were formed at a rate of about 3.3×10^3 km^3/m.y. throughout 75×10^6 years from 130 m.y. BP to 55 m.y.BP. The largest amount of volcanic rocks was formed during the time from 115 m.y.BP to 100 m.y.BP and the average volume is 4×10^3 km^3/m.y. This estimation seems to be smallest, because the volcanic activity would not have succeeded for 15 m.y. long. If we accept that

Table 9. Time relation between "Nohi rhyolite" and granitic rocks of Chubu district

m.y.	volcanic	granitic	after RGRB (1972)
60	Stage-V	Shirakawa	
70 80	Stage-II-IV	Naegi Inagawa	younger granite
90			Nohi rhyolite
100 110	Stage-I	oldre gr. ?	older granite

* CRGNR = Collaborative research group for Nohi rhyolite

Table 10. Volume of igneous rocks in the inner zone of southwest Japan

			AGE in m.y. 130~115	115~100	100~85	85~70	70~55	TOTAL
130.5° ~ 132.0°	I	V	KWANMON 2,700 SHUNAN 2,400	ABU 16,500				21,600
		P	2,000	1,000	2,500	500		6,000
132.0° ~ 133.5°	II	V	KISA 3,000	TAKADA 15,000 HIKIMI 5,000			SAKUGI 800	23,800
		P		100	30,000	10,000	15,000	55,100
133.5° ~ 135.0°	III	V	HIROMINE 500	AIOI 5,000 IKUNO 10,000 YATAGAWA 1,000			TENKADAIYAMA 200	16,700
		P	100		11,000	7,000	12,000	30,100
135.0° ~ 136.5°	IV	V	SASAYAMA 100	ARIMA 2,000 IKUNO 5,000 KOTO-I 700 OMOTANI 100		KOTO-II & III 300 KONGODOJI 50 NISHITANI 50		8,300
		P			15,000	4,000	6,000	25,000
136.5° ~ 138.0°	V	V		NOHI-I 2,000		NOHI-II~IV 15,000	NOHI-V 500 FUTOMIYAMA 1,300	18,800
		P			5,000	20,000	20,000	45,000
TOTAL		V	8,700	62,300	0	15,400	2,800	89,200
		P	2,100	1,100	63,500	41,500	53,000	161,200
(V+P)			10,800	63,400	63,500	56,900	55,800	250,400
$10^3 \times km^3$/m.y.			0.7	4.2	4.2	3.8	3.7	3.3

V : volcanic rocks, P : plutonic rocks. volume=in km^3

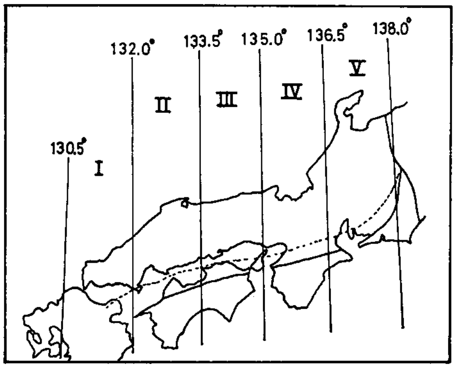


Fig. 12. Five areas of southwest Japan, divided at 1.5° interval from 130.5°E to 138.0°E.

one volcanic activity was held within 5 m.y., the production rate becomes 1.2×10^4 km^3/m.y.

In Table 11 the production rate of volcanic rocks is listed for several volcanic provinces of the circum-Pacific orogenic belt. It is clearly seen from this table that the production rate of the late Mesozoic volcanic rocks of southwest Japan is in the same order as that of the circum-Pacific orogenic volcanic rocks. This implies that the late Mesozoic volcanic activity of southwest Japan was derived by the same mechanism as the present orogenic volcanic activity which is believed to be closely connected with the sinking lithosphere plate (e.g. KUNO, 1968).

The variation diagrams showing volume versus time are drawn in Fig. 13 and 14. Figure 13 shows the individual feature of five areas of Fig. 12, and Fig. 14 shows the total feature of the whole area of the inner zone of southwest Japan. The patterns of the volume of igneous rocks in three areas of II, III and IV are almost the same (Fig. 13). In these areas, there are two peaks for the volume of volcanic rocks and older one is larger than the younger. On the other hand, in the area of I, there is one peak for volcanic rocks of old age. These features represent the eastward migration of the volcanic activity.

Generally speaking, the peak of the volume of volcanic rocks precedes that of

Table 11. Production rate of volcanic rocks of some provinces in the circum-Pacific orogenic belt.

PROVINCE	AGE (m.y.)	VOLUME ($\times 10^3 km^3$/m.y.)	AREA ($\times km^2$)	REFERENCE
Green tuff, northeast Japan	25-10	$1\sim30$	$\approx 1\times10^5$	SUGIMURA et al., 1963
Quaternary, northeast Japan	2- 0	≈ 4	$\approx 1\times10^5$	//
North Island, New Zealand	2- 0	8.6	2×10^4	HEALY (1962)
Central Andes	6- 0	≈ 10	$\approx 1.5\times10^5$	JAMES (1971)
Southewst Japan	120-60	$1\sim13$	$\approx 1\times10^5$	this work

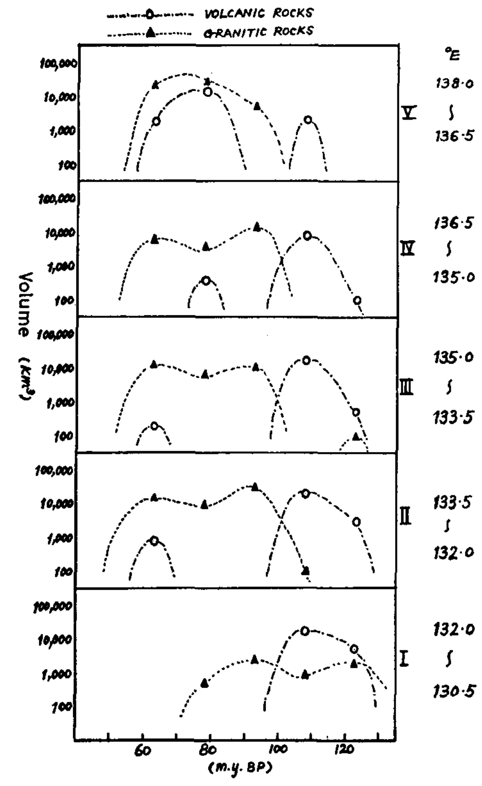


Fig. 13.

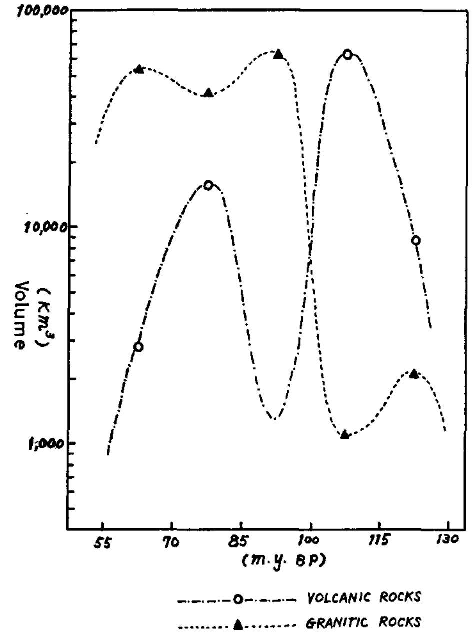


Fig. 14.

Fig. 13. Variation of estimated volume of igenous rocks versus age in five divided area. Volume is shown in log-scale. Open circles represent volcanic rocks and solid triangles are for granitic rocks.

Fig. 14. Variation of volume of igneous rocks versus age for whole area of the inner zone of southwest Japan (Ryoke metamoprhic zone is not included).

plutonic rocks. This fact indicates that plutonic rocks intrude after the eruption of the volcanic rocks through one cycle of igneous activity of volcanic-plutonic complex. This feature is clearly shown in Fig. 14, and there are two cycles of this volcanic-plutonic complex in the inner zone of southwest Japan in the late Mesozoic era. It has been pointed out that two peaks are recognized in the histogram of age data of granitic rocks in southwest Japan (KAWANO and UEDA, 1967; HAYASE and ISHIZAKA, 1967; MATSUMOTO, 1969; NOZAWA, 1970). This feature is also recognized by the volume estimations of igneous rocks shown in Fig. 14.

B-2 Space-time relations

To know the migration of the distribution area of the volcanic rocks, the locations of the volcanic rocks in three age groups are illustrated in Fig. 15. The volcanic rocks

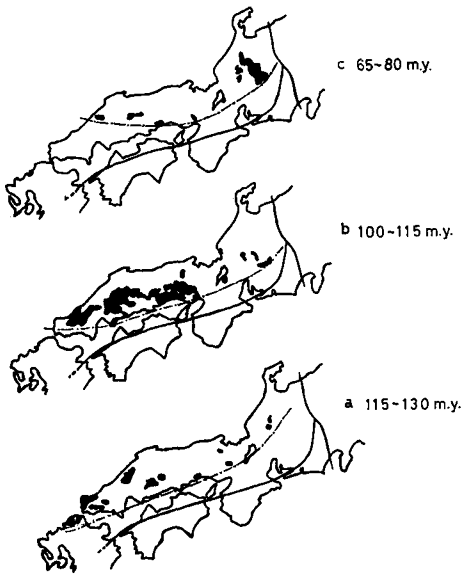


Fig. 15. Geological sketch map showing migration of volcanic activity. Black areas represent the distribution of volcanic rocks. Dash-dot line represents southern end of the distribution of volcanic rocks (volcanic front).
a: 115–130 m.y., b: 100–115 m.y., c: 65–80 m.y..

of 130–115 m.y., 115–100 m.y. and 80–65 m.y. are shown in Fig. 15-a, -b and -c, respectively. The dot-dashed lines in Fig. 15 connecting the southern edge of the distribution areas reveal some interesting features. We call this line volcanic front. Although the term of volcanic front (SUGIMURA, 1960) is commonly used for the Cenozoic orogenic belt, it may not be unsuitable to use for this case, because the late Mesozoic volcanic rocks seem to have been formed by the same mechanism as the Cenozoic orogenic volcanic rocks.

It appears from Fig. 15 that the migration of the volcanic front actually occurred. As the age becoming younger, the volcanic front migrated northward in the western part and southward in the eastern part of southwest Japan. It is also recognized that the curvature of the volcanic front of 80–65 m.y. is greater than that of 115–100 m.y. or 130–115 m.y.

The increasing of curvature of the late Mesozoic volcanic front of southwest Japan could have been caused by such effect as described by MATSUDA and UYEDA (1971). They explained on the development of arcuate shape of island festoons as follows. In such a case as schematically illustrated in Fig. 16, once a chain of island arcs starts to form, it will continue to accent its arcuate shape with angled intersections. KAIZUKA (1972) considered that the volcanic front of the present northeast Japan becomes concave at the southern and northern edges by this effect.

In Fig. 17, the thermal axis of the Ryoke metamorphic belt (MIYASHIRO, 1959; SUWA, 1961, 1973) and the volcanic front of about 110 m.y.BP are illustrated. It is noteworthy that these two lines are almost parallel. This may represent that both

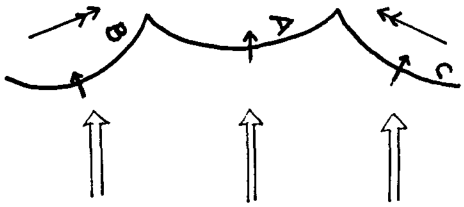


Fig. 16.

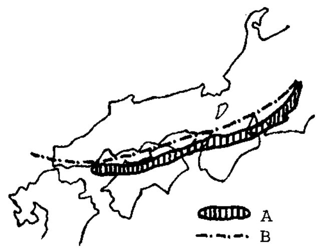


Fig. 17.

Fig. 16. Axial compression in a chain of arcs. White arrows: oceanic plate motion; small arrows: relative motion between oceanic and marginal plates; double arrows: motion of marginal sea plate double arrows: motion of marginal sea plate C and B, relative to A. (after Matsuda and Uyeda, 1971).

Fig. 17. Comparison of directions between metamorphic belt and volcanic front at middle Cretaceous. A: thermal axis of the Ryoke belt (Suwa, 1973), B: volcanic front of 115–100 m.y. BP.

of the metamorphism and volcanism occurred under the same tectonic circumstances, i.e., thermal distribution at lower crust and mantle overlying the Benioff zone, or moving rate of oceanic plate descending under southwest Japan at that time, etc. If this is the case, it is conceivable that the formation of the thermal axis of the Ryoke metamorphic belt was formed at the same time of the volcanic activity of about 110 m.y.BP. This is not incompatible with the radiometric ages of the metamorphic and granitic rocks of the Ryoke belt (ISHIZAKA, 1966, 1969).

C: Rubidium and strontium concentrations

The Rb/Sr ratio of the late Mesozoic igneous rocks obtained in the present study is between 0.05 and 24. The Rb and Sr contents range from 20.6 ppm to 434 ppm and from 18 ppm to 427 ppm, respectively. These variations of Rb and Sr contents are compatible with the characteristics that most of the late Mesozoic igneous rocks of southwest Japan are intermediate or acidic compositions. The Sr content smaller than 500 ppm for the andesitic rocks shows a typical calc-alkaline rock series.

These features are compared with other calc-alkaline rocks of the circum-Pacific orogenic belt (Fig. 18). It is clearly observed that Rb content and Rb/Sr ratio of the late Mesozoic igneous rocks of southwest Japan are somewhat higher than those of other calc-alkaline rocks, for instance, in the highly differentiated rhyolite lavas or ignimbrites of New Zealand, Rb content is not greater than 150 ppm and Rb/Sr ratio is lower than 2.0 (EWART and STIPP, 1968). This implies that the source magma of the late Mesozoic igneous rocks of southwest Japan were enriched in Rb or that the crystalization differentiation occurred strongly, comparing with other calc-alkaline rocks.

The variation of Rb and Sr contents are indistinguishable between extrusive rocks and intrusive rocks. It is noteworthy that Rb and Sr contents of the granitic rocks

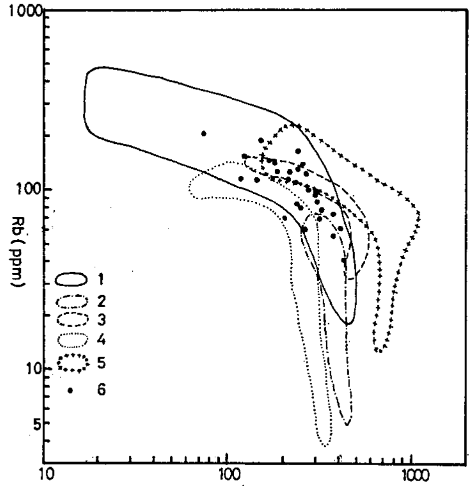


Fig. 18.

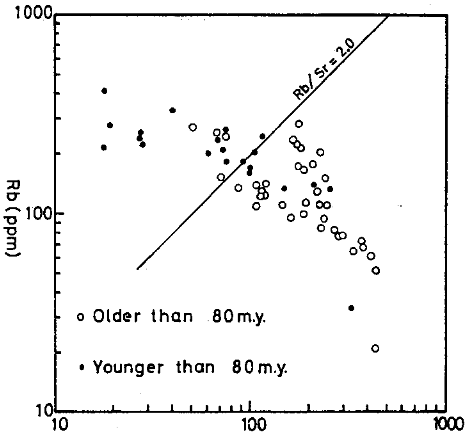


Fig. 19.

Fig. 18. Variation of Rb and Sr concentrations in some volcanic provinces in the circum-Pacific orogenic belt. 1: late Mesozoic igneous rocks in the inner zone of southwest Japan (this study), 2: volcanic rocks of Myoko, Japan (Ishizaka et al., 1977), 3: volcanic rocks of Aso, Japan (Kurasawa, 1972), 4: volcanic rocks of North Island, New Zealand (Ewart & Stipp, 1968), 5: volcanic rocks of central Andes (James et al., 1973), 6: granitic rocks in the Ryoke metamophic belt, Japan (Kagami, 1973).

Fig. 19. Comparison of the variation of Rb and Sr concentrations between older rocks and younger rocks on the basis of 80 m.y. BP.

in the Ryoke belt are plotted also in the field of the late Mesozoic igneous rocks (Fig. 18). This may represent that the petrogenesis of extrusive rocks and intrusive rocks are same.

The most distinctive feature is that the almost all specimens of large Rb/Sr ratio (>2.0) are younger than 80 m.y. (Fig. 19). These highly differentiated rocks belong to the Tenkadaiyama group, Koto-II & III and Stage-II of Nohi rhyolite. Especially, Sr content is lower than 30 ppm and Rb content is larger than 200 ppm in Koto-II & III, as noted earlier.

D: Variations in the initial Sr^{87}/Sr^{86} ratio and their petrogenetic significance

The initial Sr ratios obtained in the present study are ranging from 0.7051 to 0.7103. Available data reported previously are also in the same range (Ozima *et al.*, 1967; Ishizaka, 1971; Hattori and Shibata, 1974). The granitic rocks in the Ryoke metamorphic belt have also the initial Sr ratio in this range (Kagami, 1973; Shigeno and Yamaguchi, 1976).

These isotopic ratios are higher than that of the ocean ridge basalt of 0.7025 ± 0.0010 (Hedge and Peterman, 1970; Hart, 1971) and that of the ordinary island

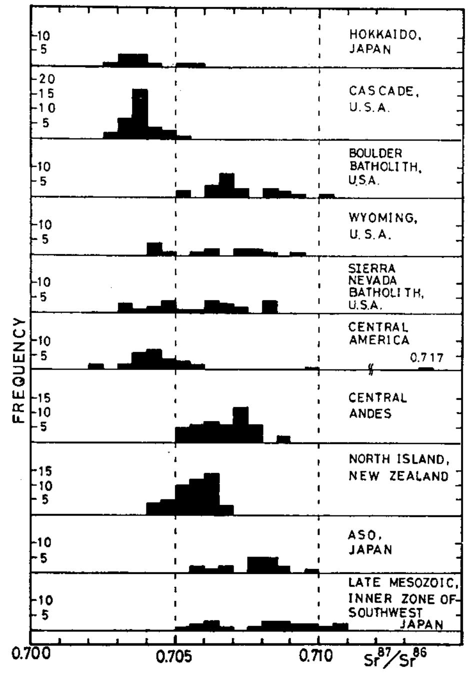


Fig. 20. Histgrams showing distribution of intitial Sr^{87}/Sr^{86} ratios of calc-alkaline rocks from several provinces in the circum-Pacific region. Hokkaido, Japan (Kurasawa & Fujimaki, 1974), Cascade, USA (Church & Tilton, 1973), Boulder Batholith, USA (Doe et al., 1968), Wyoming, USA (Peterman et al., 1970), Sierra Nevada Batholith, USA (Kistler & Peterman, 1973), Central America (Pushkar, 1968; Pushkar et al., 1971), North Island, New Zealand (Ewart & Stipp, 1968), Aso, Japan (Kurasawa, 1972), Inner zone of southwest Japan (this study; Ozima et al., 1967; Ishizaka, 1971; Kagami, 1973; Hattori & Shibata, 1974; Shigeno & Yamaguchi, 1976).

arc calc-alkaline volcanic rocks of 0.704 ± 0.001 (PUSHKAR, 1968). Another distinct feature is that the initial Sr ratio of the late Mesozoic igneous rocks of southwest Japan show a larger variation (0.705–0.710) than that of the ocean ridge basalt or island arc volcanic rocks.

Figure 20 shows the initial Sr ratios of calc-alkaline rocks from several provinces in the circum-Pacific region. It is clearly seen that there are two groups; one is characterized by lower initial Sr ratios than 0.705, such as Hokkaido, Cascade and Central America and the other by higher ratios than 0.705, such as Boulder Batholith, Wyoming and Aso. The late Mesozoic igneous rocks of southwest Japan are belonging to the latter.

In Fig. 21, initial Sr ratio is plotted against assigned age. DOE *et al.* (1968) reported that the initial Sr ratio of the Boulder Batholith increases as the age became younger. Such phenomenon, however, is not clearly observed from this figure. It is rather distinct that there are two groups of initial Sr ratios, one is higher than 0.707 and the other is lower than that. This may reflect the areal variation. The initial Sr ratios are plotted against sampling locality from west to east in Fig. 22. It is obvious that the initial Sr ratio varies abruptly at about 136°E. In the western part of the studied area, the lower Sr ratio group is observed, but it is not observed in the eastern part, beyond 136°E.

The explosion seismological observations (ASADA and ASANO, 1972) reveal an

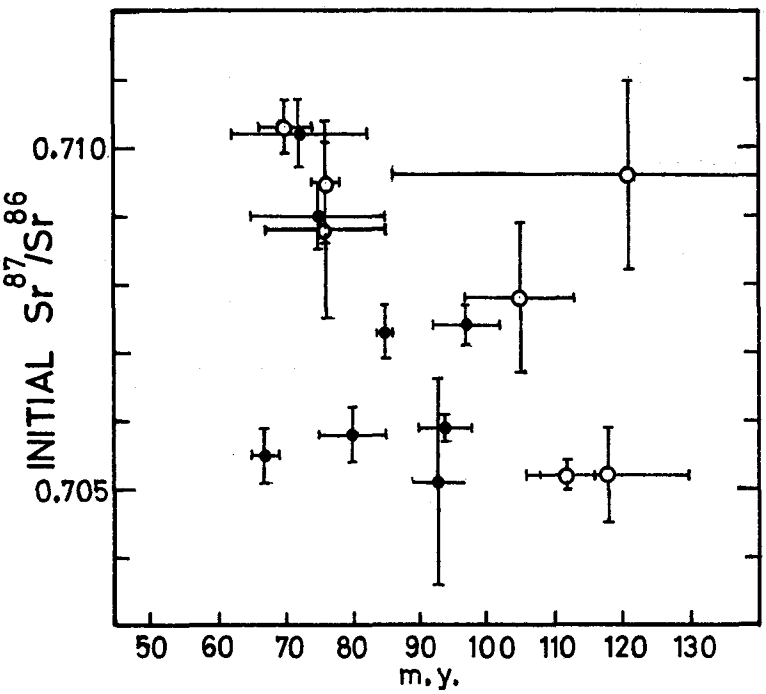


Fig. 21. Variation of initial Sr^{87}/Sr^{86} versus age obtained from isochron plot for late Mesozoic igneous rocks in the inner zone of southwest Japan. Open circles indicate volcanic rocks and solid circles are for plutonic rocks.

interesting feature. The crustal structure of central Japan (about 137°E) is distinguishable from other regions in regard to the point that so-called basaltic layer is very thin (Aoki *et al.*, 1972). Further, the lower crustal structure seems to change at about 136°E from west to east along the line of Kurayoshi (134°E) and Hanabusa (136.5°E) (Sasaki *et al.*, 1970). This change corresponds to the variation of the initial Sr ratios of the late Mesozoic igneous rocks. Therefore, it is conceivable that the initial Sr ratios are correlative with the crustal structure, mainly of its lower part.

Judging from the fact that the observed initial Sr ratios are distinctly higher than that of the upper mantle (<0.705) and that there is a correlation between initial Sr ratios and lower crustal structure, it is conceivable that the source magma of the late Mesozoic igneous rocks of southwest Japan was derived from the lower crust.

Under the ordinary geothermal gradient, it is difficult to assume the melting in the lower crust at about 20–30 km depth. In the late Mesozoic era, however, the geothermal gradient might be larger in southwest Japan, as deduced from that the Ryoke metamorphism occurred at that time. In the high temperature and low pressure type metamorphic belt such as the Ryoke blet, the thermal gradient is greater

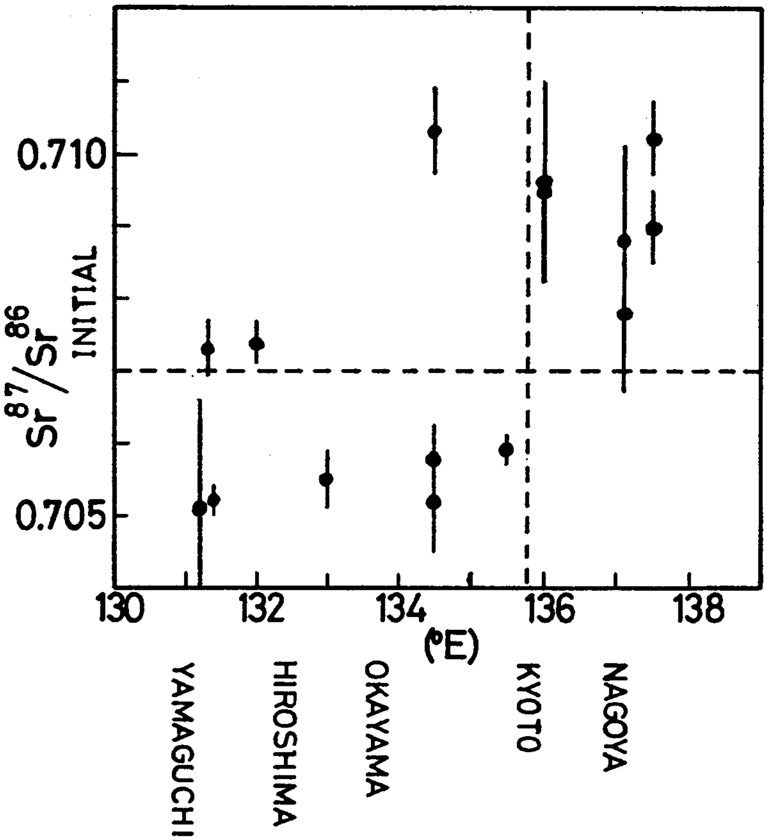


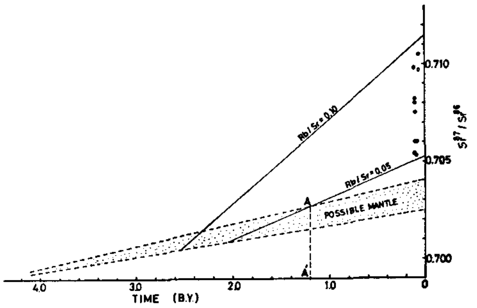
Fig. 22. This figure shows areal variation of intial Sr^{87}/Sr^{86} ratio. Initial ratios in the region east from 136°E are higher than 0.7070.

than 25°C/km and in some areas it reachs over 50°C/km (MIYASHIRO, 1972). Therefore it is well expected that the partial melting may have occurred in the lower crust of southwest Japan during the late Mesozoic era to produce the magma.

The Rb/Sr ratios of the late Mesozoic igneous rocks of southwest Japan are higher than those of other orogenic igneous rocks of the circum-Pacific region and this fact reveals differentiated feature of original magma, as discussed before. This character corresponds to the model that the source magma derived from lower crust rather than from upper mantle.

RINGWOOD and GREEN (1966) demonstrated that the lower crust of so-called basaltic layer should be intermediate composition and not basaltic. So, we assume the Rb/Sr ratio of the lower crust to be between 0.05 and 0.10 which is the value of the andesitic rocks. If we consider the simple model of the lower crust separated from the mantle, the lower crust should have an "age" older than 1.2 b.y. (b.y.=billion years)

Fig. 23. Variation of Sr^{87}/Sr^{86} as a function of time in the mantle and lower crust. The field between two dashed lines is for possible mantle region. Solid lines represent second-stage lower crust evolutionary trends. These solid lines meet the possible mantle region at older than 1.2 b.y. (A-A′). Open circles are observed initial Sr^{87}/Sr^{86} ratios.



as illustrated in Fig. 23 (indicated by line A-A'). The inference that some calc-alkaline rocks were derived from the source of old age has been proposed by some investigators. Doe *et al.* (1968) demonstrated by the determinations of U-Pb system that the granitic rocks of the Boulder Batholith (Sr^{87}/Sr^{86}=0.705–0.710) should be derived from a 2.0 b.y. old source material. From Pb-Pb age, the andesitic rocks of Wyoming (Sr^{87}/Sr^{86}=0.704–0.709) were considered to be derived by the partial melting of some 3.0 b.y. old source region (Peterman, Doe and Prostka, 1970). Therefore, the old age model for the lower crust of southwest Japan may not be an irrelevant one, although the "age" older than 1.2 b.y. is not fixed one, because Rb/Sr ratio for lower crust may be variable.

The geological relationship between Korean Peninsula and Japanese Islands is often refferred in the discussions of the geological development of Japanese Islands. On the Precambrian gneiss of South Korea, Hurley *et al.* (1973) reported that the age of some rocks are at least as old as 2.0 b.y. and other rocks show the age of 9.0–1.4 b.y. Some U-Pb zircon ages of South Korea are about 2.15 b.y. (Gaudette and Hurley, 1973). These ages are very similar to those of gravels of the Kamiaso congromerates of Japan which are about 2.0 b.y. (Shibata and Adachi, 1974). These correlative data would support the possibility that the lower crust of southwest Japan were formed at some time in the Precambrian.

V Conclusions

The results obtained from the Rb-Sr isochrons reveal some interesting features of the late Mesozoic igneous activity in the inner zone of southwest Japan and make it possible to offer the quantitative discussions. The conclusions obtained from the present study are summarized as follows.

1. Igneous activities occurred episodically. Volcanic rocks erupted at 120–130 m.y., about 110 m.y. and 70–80 m.y. Granitic rocks intruded at about 80–90 m.y. and 60–70 m.y.
2. Igneous rocks were generated in the inner zone of southwest Japan at the average

rate of 3.3×10^3 km^3/m.y. throughout the Cretaceous. At the most active time, the production rate seems to have reached over 10^4 km^3/m.y.

3. Rubidium and strontium contents of the late Mesozoic igneous rocks exhibit a typical calc-alkaline nature with rather high Rb/Sr ratio.
4. Initial Sr^{87}/Sr^{86} ratios obtained in this study range from 0.7051 to 0.7103.
5. The characteristics of the Rb and Sr contents and initial Sr^{87}/Sr^{86} ratios in plutonic rocks and volcanic rocks resemble each other. This implies that these rocks belong to one large volcano-plutonic complex.
6. The initial Sr ratios and the Rb and Sr contents are most reasonably explained by the model that the original magma was formed by the partial melting of the very old lower crustal materials.

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Appendix-I Sampling Localities

Sample No.	Longitude	Latitude	Place	1/50,000 map name
YAMAGUCHI DISTRICT				
YM04	131°35′E	34°18′N	Chyomonkyo	Chyomonkyo
YM06	131°40′E	34°24′N	Kajigaya	Tokusanaka
YM08	131°42′E	34°26′N	Tayoshi	//
YM09	131°45′E	34°26′N		//
YM18	131°47′E	34°38′N		Nichihara
YM23	131°33′E	34°34′N	Takakurose	Susa
YM27	131°20′E	34°04′N		Ogori
TM01	131°40′N	34°35′N	Ogawa	Susa
HIMEJI DISTRICT				
HM01,02,03 and 06	134°28′E	34°48′N	Naba	Banshu-Akoh
HM07	134°23′E	34°50′N		Kamigori
HM09	134°21′E	34°45′N	Maki	Banshu-Akoh
HM11	134°22′E	34°50′N	Kurosawa	Kamigori
HM14	134°25′E	34°53′N		//
HM15	134°18′E	34°55′N	Nishishinjuku	//
HM17	134°16′E	34°55′N		//
HM21	134°15′E	34°52′N	Minamidani	//
HM22	134°25′E	34°44′N	Maruyama	Banshu-Akoh
KOTO DISTRICT				
KT01	136°06′E	35°06′N	Binwariyama	Omihachiman
KT03	136°05′E	35°09′N	Kakuyokuyama	//
KT06	136°04′E	35°10′N	Chyomieji	//
KT08	136°05′E	35°11′N		Hikone Seibu
KT09	136°09′E	35°08′N		Omihachiman
KT10 and 11	136°17′E	35°10′N		Gozaishoyama
KT25	136°22′E	35°06′N		//
KT32	136°18′E	35°10′N		Hikone Tobu
KT40,41,42,43 and 45	136°18′E	35°10′N		Gozaishoyama
NOHI DISTRICT				
NH01	137°15′E	35°39′N		Kanayama
NH03 and 04	137°14′E	35°38′N	Usuno	//
NH05	137°14′E	35°39′N	Tokuda	//

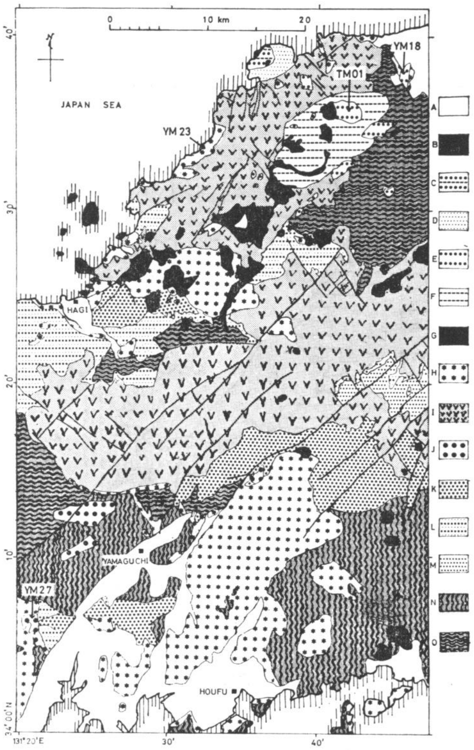

Fig. AP-1

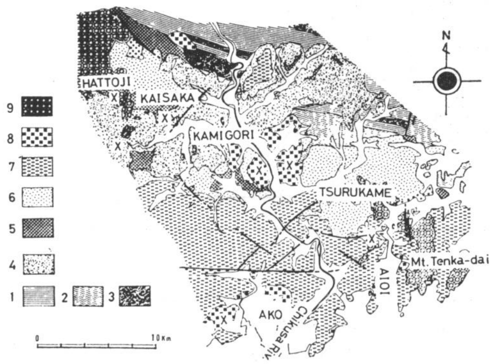

Fig. AP-2

Fig. AP-1; Generalized geological map of Yamaguchi district (after Yamaguchi Prefecture (1968) and Murakami, personal communication) and sampling localities.

Explanations

Quaternary

A: sedimentary rocks B: basalt

Tertiary

C: gabbro D: shale

E- plutonic rocks of the Tamagawa group (P-IV)

F: volcanic rocks of the Tamagawa group (V-IV)

G: basaltic andesite

Cretaceous

H: granitic rocks (P-III) H: granitic rocks (P-III)

I: volcanic rocks of the Abu group (V-II)

J: plutonic rocks of the Shunan group (P-I)

K: volcanic rocks of the Shunan group (V-I)

L,M: Kwanmon group

Pre-Cretaceous

N: Sangun metamorphic rocks O: Paleozoic basement

Fig. AP-2; Generalized geological map of Aioi, Akoh and Kamigori area showing sample localities (X) (after Kishida & Wadatsumi, 1967).

Explanations

Basement: 1; Paleozoic, 2; phyllite, 3; intrusive rocks of Yakuno type

Aioi group: 4; Kamigori formation, 5: andesite of Tsurukame formation, 6; rhyolitic welded tuff of Tsurukame formation, 7; Akoh formation

8: Harima granite, 9: Tenkadaiyama group

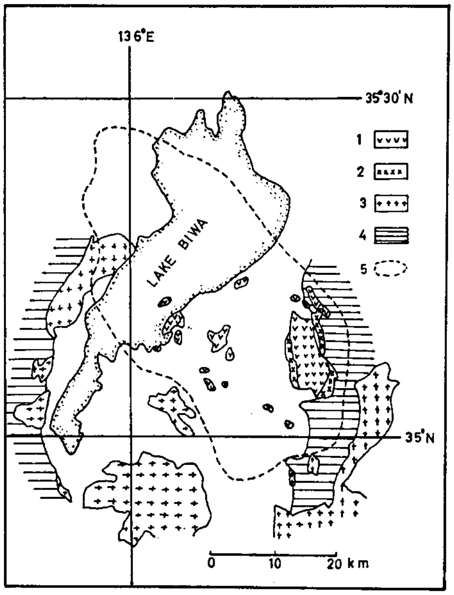

Fig. AP-3

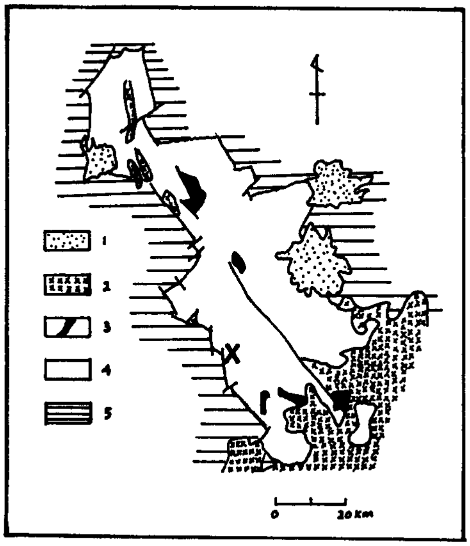

Fig. AP-4

Fig. AP-3; Generalized geological map of Koto district (after Kawada, 1969; Mimura, 1972)
Explanations
1: Koto rhyolite (Koto-I, II and III)
2: intrusive rocks related to Koto rhylite,
3: granitic rocks, 4: Paleozoic basement,
5: supposed original distribution area of Koto rhyolite

Fig. AP-4; Generalized geological map of Nohi rhyolite mass (after Yamada, Kawada and Morohashi, 1971)
Explanations
1: recent volcanic rocks, 2: Cretaceous granitic rocks, 3: intrusive rocks, 4: Nohi rhylite, 5: basement rocks, X: sampling locality

Appendix-II Sample Separation

Biotite in granitic rocks was separated using methylene iodide-acetone mixture. Plagioclase and K-feldspar were separated using bromoform-ethyl alchol mixture.

Sample separations of volcanic rocks were handled as follows.

HM06: A sieved sample (100–200 mesh) was used for magnetic and density separations. Repeated passes were made through the Frantz magnetic separation with a tilt angle of the through of 10° and 15° inclination. Detailed procedures are illustrated in Fig. AP-5.

Obtained separated fractions #Fr-1 and #Fr-2 are both matrix components. #Fr-3 is plagioclase of phenocrysts. Fr-4 is a mixture of K-feldspar and albite of phenocrysts.

The approximate ratio of Rb/Sr measured by XRF are as follows: Fr-1 =2.9, Fr-2=1.4, Fr-3=0.3, Fr-4=0.7.

HM17: After separating the phenocrysts from groundmass by the Frantz, the fractions of plagioclase+quartz (Pl+Qz) and K-feldspar (Kf) were separated using bromoform-ethyl alchol mixture.

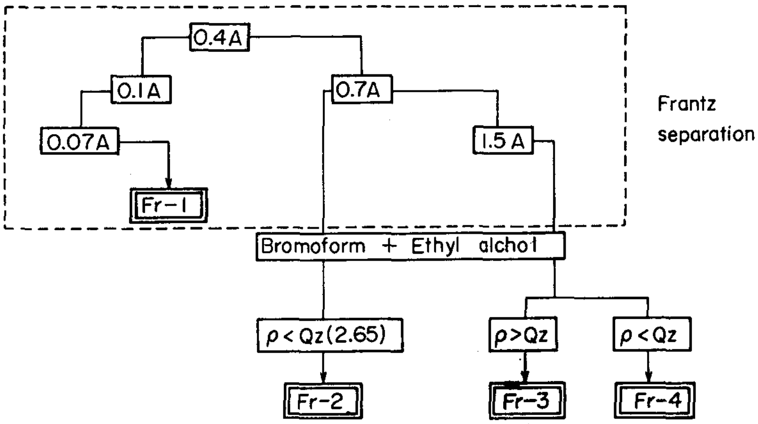

Fig. AP-5; Sample separation procedure of HM06

HM21: A sieved sample (60–150 mesh) was used. The Frantz was operated with a tilt angle of 10° and 21° inclination. Detailed procedures are illustrated in Fig. AP-6.

Three fractions (#M-4, #Pl and #K-f) obtained from this procedures were used for Rb-Sr analysis. #M-4 is matrix component and #Pl and #K-f are plagioclase and K-feldspar phenocrysts respectively.

Another fractions obtained by hand picking is Pm which is a aggregation of pumice lens.

The approximate ratio of Rb/Sr measured by XRF are as follows; M-1=1.7, M-2=1.8, M-3=2.1, M-4=3.2, M-5=3.0, M-6=2.1, K-f=2.8 , Pl=0.4, Mat=2.9, Pm=3.3.

KT09: Three sieved samples were used.

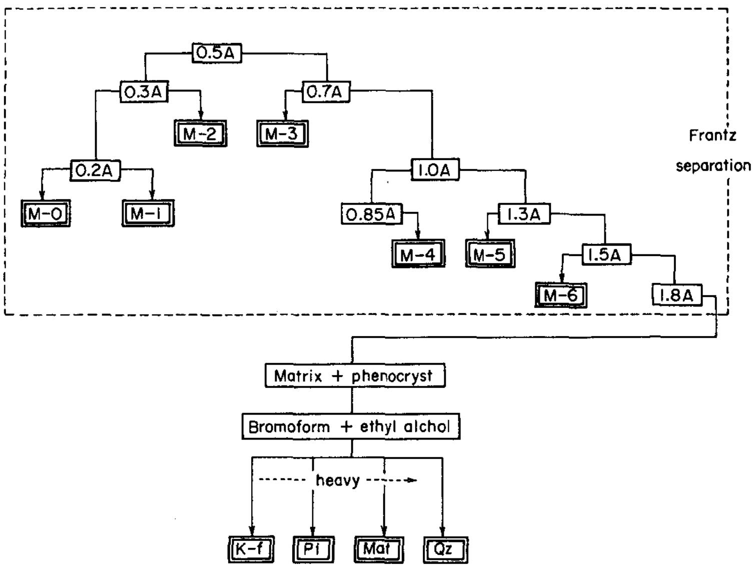

Fig. AP-6; Sample separation procedure of HM21

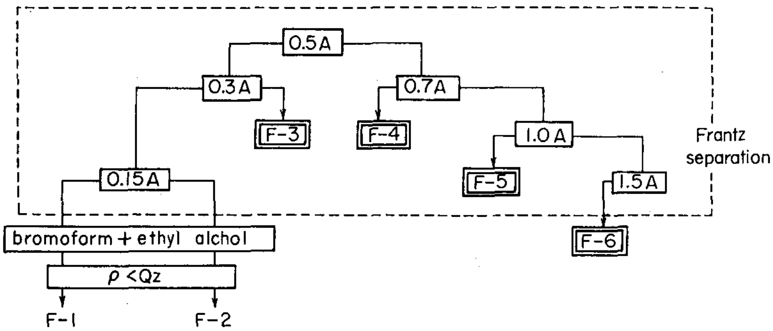

Fig. AP-7; Sample separation procedure of KT09

a) 32–60 mesh ;This sample was used for phenocryst separation. Four density fractions lighter than quartz were obtained, Fd-A, Fd-B, Fd-C, and Fd-D from light to heavy respectively. The heavier part than quartz are almost matrix component.

b) 60–200 mesh; This sample was used for the separation of matrix part. The Frantz was operated with a tilt angle of 5° and 20° inclination. Detailed procedures are illustrated in Fig. AP-6.

c) smaller than 200 mesh; This smaple was used for Rb-Sr determination with no treatments. Sample name is #-200 m.

The approximate ratio of Rb/Sr measured by XRF are as follows; Fd-A=1.3, Fd-B=1.4, Fd-C=1.3, Fd-D=1.8, -200 m=0.9, F 1=1.6, F-2=2.0, F-3=2.3, F-4=1.4, F-5=1.4, F-6=1.3.

Four fractions ,Fd-D, -200 m, F-1 and F-2, were used for Rb-Sr measurement.